Determining the Efficiency of Converting Magnetar Spindown Energy into Gamma-Ray Burst X-ray Afterglow Emission and Its possible Implications

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Abstract

Plateaus are common in X-ray afterglows of gamma-ray bursts. Among a few scenarios for the origin of them, the leading one is that there exists a magnetar inside and persistently injects its spin-down energy into an afterglow. In previous studies, the radiation efficiency of this process is assumed to be a constant $\gtrsim 0.1$, which is quite simple and strong. In this work we obtain the efficiency from a physical point of view and find that this efficiency strongly depends on the injected luminosity. One implication of this result is that those X-ray afterglow light curves which show steeper temporal decay than t^{-2} after the plateau phase can be naturally understood now. Also, the braking indexes deduced from afterglow fitting are found to be larger than those in previous studies, which are more reasonable for newborn magnetars.

Key words: gamma-ray burst: general – radiation mechanisms: general – stars: neutron

1. Introduction

Ever since the launch of the Swift satellite, X-ray afterglows of dozens of GRBs have been found to exhibit plateau features, which are thought to be the signature of a long-lasting energy injection from the central engine (Zhang et al. 2006). The injected energy probably comes from the spindown power from a newborn magnetar (Dai & Lu 1998; Zhang & Mészáros 2001).

The origin of plateaus in X-ray afterglow light curves is still under debate, and basically we would expect two different kinds. The first kind is called external plateaus that originate from external shocks. In this case the energy injection comes from a late kinetic-energy-dominated shell interacting with a preceding expanding fireball (Rees & Mészáros 1998). Alternatively, if the X-ray plateau is internal, it can be produced by an internal energy dissipation in the magnetar wind. In this case the spindown power is mediated by an initially cold, Poynting-flux dominated wind that can be gradually accelerated as its magnetic energy dissipates internally via magnetic reconnection (Spruit et al. 2001). There will be high-energy emission in this process (Beniamini & Giannios 2017; Xiao & Dai 2017) that can be responsible for the X-ray plateau.

In this paper we focus on the latter case and calculate the X-ray radiation efficiency in this physical model. Previous works usually assumed that η_X is constant (Lü et al. 2019). We think better of this assumption here.

2. Theoretical analysis

A newborn magnetar loses its rotational energy via gravitational-wave and electromagnetic radiation, whose angular velocity evolution can be generalized as follows (Lasky et al. 2017),

$$\dot{\Omega} = -k\Omega^n, \tag{1}$$

where $\Omega = \Omega(t) = 2\pi/P(t)$ is the spin angular velocity, and k and n represent a constant of proportionality and the braking index of magnetar respectively. The solution of Eq.(1) is (Lasky et al. 2017; Lü et al. 2019)

$$\Omega(t) = \Omega_0 \left(1 + \frac{t}{\tau}\right)^{\frac{1}{1-n}}, \tag{2}$$

where Ω_0 is the initial angular velocity and $\tau \equiv \Omega_0^{1-n}/[(n-1)k]$ is the spin-down timescale. The injected energy into the afterglow comes from the magnetic dipole torque whose luminosity is $L_{\rm EM} = B^2R^6\Omega^4/6c^3 = L_0(1+t/\tau)^{4/(1-n)}$, where $L_0 \equiv B^2R^6\Omega_0^4/6c^3 = 1.0 \times 10^{49} B_{15}^2 R_6^6 P_{-3}^{-4}\,{\rm erg\,s^{-1}}$. Throughout this paper the notation $Q = 10^x Q_x$ in cgs units is adopted and the radius of magnetar is assumed to be $R = 10^6\,$cm. The observed X-ray plateau luminosity is $L_X = \eta_X L_{\rm EM}$ by introducing an efficiency η_X, where η_X could evolve with time.

3. Afterglow light-curve fitting

3.1. X-ray radiation efficiency

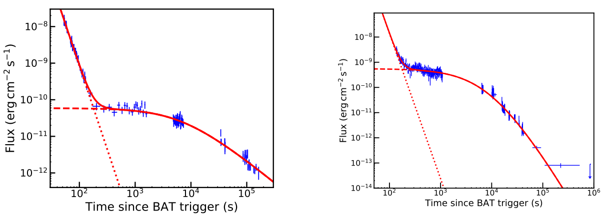
Because η_X is dependent on the observational properties such as the energy range of the instrument and redshift of the source, it is not easy to derive an analytical relation. Instead, we can carry out an empirical polynomial fitting to obtain the X-ray efficiency η_X as a function of injected electromagnetic luminosity $L_{\rm EM}$, which are

$$\begin{aligned} \log\eta_X &= -0.042(\log L_{\rm EM})^2 + 3.81\log L_{\rm EM} - 87.29, \\ \log\eta_X &= -0.059(\log L_{\rm EM})^2 + 5.61\log L_{\rm EM} - 134.60, \\ \log\eta_X &= -0.030(\log L_{\rm EM})^2 + 3.10\log L_{\rm EM} - 80.28, \\ \log\eta_X &= -0.0034(\log L_{\rm EM})^2 - 0.016\log L_{\rm EM} - 10.89, \\ \log\eta_X &= -0.011(\log L_{\rm EM})^2 - 0.75\log L_{\rm EM} + 4.78, \end{aligned} \tag{3}$$

for $\Gamma_{\rm sat} = 10^2,\ 10^{2.5},\ 10^3,\ 10^4,\ 10^5$ respectively.

3.2. Individual cases fitting

Taking $(A, \alpha, L_0, n, \tau)$ as parameters, now we can do a Bayesian Monte-Carlo fitting using MCurveFit package (Zhang et al. 2016). The best-fitting parameters are shown in Table 1. As an example, we show the light curve fitting to GRB 100615A and GRB 150910A for $\Gamma_{\rm sat} = 10^3$ case in Figure 1.



(a) The fitting result of X-ray afterglow light curve for GRB 100615A.

(b) The fitting result of X-ray afterglow light curve for GRB 150910A.

Fig. 1. Two examples of afterglow fitting results.

3.3. Comparison with previous works

Since our fitted X-ray efficiency is less than 0.1, the values of L_0 are universally larger than those in Lü et al. (2019). Moreover, we find that the deduced braking indexes are also universally larger in this work. The central position of the distribution on n is also shifted to a larger value.

Table 1. The best-fitting values for the five parameters using Bayesian Monte-Carlo method.

(a) Parameters for GRB 100615A

Parameter	Allowed range	Best-fitting value
$\log A$	[40, 100]	$57.77^{+0.16}_{-0.19}$
α	[0, 15]	$4.56^{+0.084}_{-0.098}$
$\log L_0$	[42, 52]	$48.97^{+0.025}_{-0.036}$
n	[1, 7]	$4.84^{+0.24}_{-0.24}$
$\log\tau$	[1, 10]	$3.78^{+0.11}_{-0.098}$

(b) Parameters for GRB 150910A

Parameter	Allowed range	Best-fitting value
$\log A$	[40, 100]	$61.07^{+0.88}_{-0.60}$
α	[0, 15]	$5.63^{+0.40}_{-0.27}$
$\log L_0$	[42, 52]	$49.87^{+0.0093}_{-0.0065}$
n	[1, 7]	$2.55^{+0.082}_{-0.070}$
$\log\tau$	[1, 10]	$3.82^{+0.038}_{-0.048}$

4. Conclusions

In this paper we have revisited the scenario that a GRB X-ray afterglow is powered by a continuous energy injection of a newborn magnetar. For those X-ray plateaus that have internal origins, we start from the radiation process induced by the magnetic energy dissipation within the magnetar wind to calculate the X-ray radiation efficiency. This approach is much more realistic and reasonable than the commonly assumed constant efficiency. We have found that the X-ray radiation efficiency depends on the injected luminosity. This relation has an important impact on the temporal decay index after the plateau phase, namely, making β deviate from -2.

This relation has an implication that the braking index deduced from afterglow light-curve fitting should be reconsidered with care. We have have compared our results with Lü et al. (2019). The braking indexes are larger, and the number of cases with $n < 3$ is much less than that of their work.

The X-ray radiation efficiency depends strongly on the saturation Lorentz factor, which is equivalent to initial magnetization. In this sense, constraining σ_0 from the X-ray afterglow plateau may be possible in the future.

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